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SURFACE MOUNT SOLDER JOINT ISSUES IMPACTING AVIONIC INTEGRITY

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INTRODUCTION

This paper addresses some issues impacting surface mount solder joint life. Solder joint life expectancy depends on the level of stress experienced and the number of cycles of stress. Stress levels in the solder joint or surface mount fillet are related to deflections during vibration in the board and differential deflections occuring as a result of differences in thermal coefficients of expansion between the components and the board. After a finite number of deflections between board and components, fatigue failures occur. Service life within a surface mount solder fillet follows mechanical failure models. These models predict failure at a predetermined number of cycles for different stress levels in the solder fillet.

This paper specifically addresses multiple solder issues impacting avionic integrity. These topics are fatigue in surface mount devices, castellations and surface finishes, life predictions, design criteria, manufacturing processes and controls, accelerated fatigue testing, and quality assurance provisions for solder joints. Each topic will be introduced with a question expressing a concern relating to avionics integrity and a discussion relating to each topic follows.

FATIGUE IN SURFACE MOUNT DEVICES

How has fatigue of surface mount solder fillets been addressed in the design process?

Thermal cycling induces low cycle fatigue and is the predominant failure mode in surface mount devices (1). In comparison with leaded devices inserted in plated-through-holes, surface mounted leadless devices have a limited physical structure to distribute the stresses and no leads to provide compliance. Strength of the fillet is limited because of its limited size and altered physical shape compared to a joint in a leaded component. In order to achieve the needed solder joint life, the control of solder grain size and structure is required. Improvements in solder fatigue life have been shown to occur when a small grain structure initially provides uniform solder joint deformation over thermal excursions (2). The most prevalent failure mechanism is plastic slip deformation (1) and generally occurs when an initially small grain size is not achieved.

Solder joint cyclic fatigue failures take place through an accumulation of cyclic fatigue damage. Failure of the solder joint takes place when a crack forms in the solder and with additional cycling the crack grows to the point where electrical continuity is lost (3).

Characterization of the solder joint fatigue life can be expressed through a hysteresis loop in a shear-stress, shear-strain plane where the area is the visco-plastic strain energy density lb/in^2 per cycle, (delta U) shown in Figure 1 (3). Leadless surface mount solder attachments have constant stress envelopes determined by the solder yield strength. The maximum strain in leadless and leaded surface mount attachments is governed predominately by thermal expansion mismatch (3).

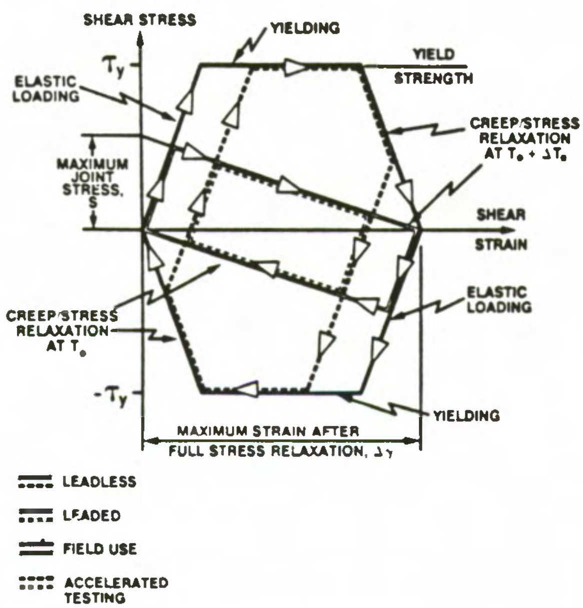

Figure 1. Hysteresis Loop (3)

Also, during thermal cycling of leadless surface mount attachments, near complete stress relaxation occurs at most use temperatures (4). Just the opposite occurs for leaded surface mount attachments, where the stresses are reduced when lead compliance is sufficient to accomodate high cyclic temperature excursion and long dwell times (4).

Fatigue of both leadless and leaded surface mount attachments results in intermittent electrical failures. Electrical intermittents in a system are the main manifestations of solder joint fatigue fractures and initially may represent less than one microsecond duration (4). Multiple thermal or vibrational cycles are necessary for complete electrical contact to be broken (4). This can explain many of the re-test-OK problems experienced in fielded avionic systems.

SOURCES OF LOW CYCLE FATIGUE IN SURFACE MOUNT DEVICES

What are the sources of low cycle fatigue in surface mount devices and what options exist for the designer?

Reliability problems result from mismatches in thermal expansion coefficients occurring during thermal cycling while boards are operating. Reliability problems also occur when the solder responds to thermal mismatch strains and stresses through time dependent plastic deformation. The predominant fatigue mechanism results from plastic rather than elastic strain. Creep and stress relaxations convert elastic strains to plastic deformations after sufficient time, temperature, and stress are applied to the joint. Plastic deformations dominate in fatigue failures of solder joints except where very rapid cycling occurs without dwell or hold times. Reducing the dwell time and area of the hysteresis loop can reduce the failure potential (4).

Additionally, differences in temperature expansions result from power dissipations within the component, and the coefficient of thermal expansion (CTE) differences take place between the component, the solder, and the board. Differing rates of power dissipations also affect thermal expansions in the board (5). Portions of the board in the vicinity of a high power compon-

ent will be heated and expanded at higher rates and reach higher temperatures than other areas of the board resulting in board warpage.

A further source of fatigue in solder joints is that thermal operating temperatures of most joints is at least half of the absolute melting point of solder. This allows creep and fatigue processes to interact during thermal cycling (8). Processes such as these contribute to the solder failure at low strain. Solder failure modes include fatigue crack initiation and propagation, or a combination of modes which result in nonlinearities between fatigue life (log) and strain range (log) (6).

These solder failure modes are seen in high lead content solders such as 4 percent tin by weight 96 percent lead by weight (4/96). In 4/96 an enhanced susceptibility to fatigue cracking occurs when tensile hold-times induce creep (6). Also, when operating at temperatures half the absolute melting point of solder, a failure mode commonly found in 63/37 solder is the coarsening of the microstructure which results in deformation bands parallel to the joint interfaces. Further, the coarsening and subsequent failure of 60/40 is influenced primarily by thermal cycles and secondarily by the exposure at high temperatures near or above 80 degrees Celsius (7). When 60/40 solder is stressed in tension rather than shear, the coarsened bands do not appear and failure occurs through rapid cracking of the brittle intermetallic layer (7).

Thermal expansion mismatch is also a source of fatigue in solder joints. This thermal mismatch in materials depends on power and heat dissipation. Temperature changes produced between the powered-off and powered-on conditions may be as much as 100 degrees Celsius. Some microstructural changes also occur in solder inevitably as it is cycled and aged, further complicating the long term deformations. Solder responds to applied stress and strains by time dependent plastic deformations. Metals undergoing cyclic strains accumulate fatigue damage. This fatigue damage, due to plastic strain, is significantly larger than fatigue damage from elastic strain (8).

Another source of fatigue in solder joints is repeated thermal shock from soldering/desoldering which contributes to failures of solder joints, connections, lifting of microcircuit chips from base materials, and delamination.

Still another source of thermal expansion fatigue in solder joints results when board and leadless surface mount device expansion coefficients are matched but there are differential temperatures between the ceramic chip carrier and the board due to internal heating of the part. The differing expansion rates result in cyclic strains in the solder joint during power cycling. Temperature differences from the power-on and power-off condition of the leadless ceramic chip carrier (LCCC) and the printed circuit substrate (PCS) can produce substrate warpage (9).

CASTELLATIONS AND SURFACE FINISHES

In what way do castellations and surface finishes affect the strength of solder joints?

Castellations are radial features on the edge of a ceramic chip carrier (10). They are metallized to provide an appropriate surface for soldering the chip carrier to the board (11). Generally castellations are on all four edges of the

chip carrier and each lies within the termination area for direct attachment to a land on a packaging and interconnecting structure. Castellated leadless chip carriers provide reliable solder attachments only for small component sizes and where thermal cycles are not extreme. The highest failure probability in castellated solder connections is on the corner solder joints (2 on chip resistors, 4 on small outline packages, and 8 on chip carriers) (11).

Lack of consistency from manufacturer to manufacturer of the physical dimensions and shape of the castellations and the hand dipped pre-tin process contribute greatly to the variability within the product and the difficulty in achieving life. Alignment of surface mount devices to solder pads on the board is also important in meeting the required life (11). Each of these issues should be addressed during the design process.

LIFE PREDICTIONS

<u>What life prediction models can be used to assess the number of fatigue cycles to failure in surface mount solder fillets?</u>

Fatigue damage laws provide reliability predictions for surface mount solder fillets (3). The cumulative stored visco-plastic strain energy per cycle provides fatigue damage with the fatigue life in cycles (N) (3)

$$N = a\ \mathrm{ABS}(\text{delta } U)^{1/b} \qquad \text{Eq. 1}$$

where a is a material constant
b is -0.5 to -0.7 for metals

The Manson-Coffin plastic strain fatigue life relationship is similar. The only difference is the substitution of plastic strain range delta G_p for visco-plastic strain energy per cycle.

$$N = a\ \mathrm{ABS}(\text{delta } G_p)^{1/b} \qquad \text{Eq. 2}$$

where delta G_p is the cyclic plastic strain range

Surface mounted leadless components made of 60/40 Sn/Pb or eutectic Sn/Pb solder have been shown to follow the relationship

$$N = 1/2\ \mathrm{ABS}(\text{delta } G_p/0.65)^{1/b} \qquad \text{Eq. 3}$$

where b = -0.442 - 6E-4(TB) + 1.74E-2 ln(1+360/t)

TB = mean solder joint temperature in degrees C computed by

0.25 (component temp + substrate temp + 2(off cycle temp))

t = half cycle dwell time (3)

The wear out mechanism of solder joints from cyclic fatigue failures have a Weibull distribution. The Weibull distributions for solder have Weibull slopes B of approximately 2 for leaded component attachments and B of approximately 4 for leadless attachments. The life is governed by (3)

$$N_2 = ((-n\ln 2)/\ln(1-FP))^{1/b}\ N_1 \qquad \text{Eq. 4}$$

where n = the number of identical components

N_1 = the expected product service life or design life, expressed in cycles of operation

FP = the acceptable cumulative failure probability for the component under consideration after N cycles

B - the Weibull distribution slope (3)

N_{β} - the design mean fatigue life at 50% of the cycles to failure

In components with many solder fillet connections, only the solder joints on the edges (8 on chip carriers, 2 on chip resistors, and 4 on small outline packages), have the highest potential for failure. The other solder fillet connections experience significantly less cyclic fatigue damage (3).

DESIGN CRITERIA

<u>What design criteria affect the strength of solder joints?</u>

Whether using leadless or leaded chip carriers, preparation and conditioning of parts to be soldered are critical factors which should be considered prior to assembly. Fundamentally soldering is a joining process, much like welding in metals or adhesives in composites. When a joining process goes awry, the first order of business is to physically correct the surface chemistry of the surfaces to be joined. However, in electronics, the first action is typically to change the flux and chemically treat/clean the material -- a cultural difference. The terminal or lead cleanliness is of great importance. Solderability of the various terminals should be verified by using quantitative test methods (11).

Component leads create standoff heights in manufacturing, aiding the removal of soldering fluxes (11). Standoff height should also be maintained for cleaning of the board in leadless devices. Planarity of leads should be maintained, and the alignment and placement position of leadless chip carriers on boards is critical to reliability (11).

In leadless package metallizations, pretinning or thin solder coating allows the terminals to be tested for solderability before assembly. Thick solder bumps added to the terminals increase the chip carrier standoff height providing compliancy to the solder joint relieving the effects of thermal expansion and improving the ability to clean the joint (11).

MANUFACTURING PROCESSES AND CONTROLS

<u>What manufacturing processes are used to control solder joint life?</u>

Solder joint life for electronic components attached to surface mounted printed circuit substrates require attention during manufacturing (3).

Methods and automated systems in the manufacture of solder joints are needed to produce the product efficiently, rapidly, repeatedly, and reliably over any desired length of time (12). Automated mass-soldering uses one machine for many soldering operations to reduce the number of personnel and the associated labor costs.

The first stage in automated mass-soldering is the application of flux which aids the solder in wetting the surfaces. A preheating stage follows, evaporates most of the solvent flux and also minimizes the thermal shock to the printed circuit board and components during soldering. The last stage of automated soldering is to solder the components to the printed circuit board (PCB).

The simplest type of automated soldering is dip soldering in which the assembly is placed into a molten solder bath at a depth which forms

the required joints. Drag soldering differs from dip soldering only in that lateral motion is used between the circuit board and the surface of a static solder bath. Finally, in wave soldering, the assembly passes through the crest of a standing wave of solder (12).

Dip soldering can be used to presolder or pretin the leads or terminations of a wide range of electrical components such as diodes, transistors and coils. When using automated soldering processes, pretinning is necessary to assure satisfactory joining. Component solderability of automated processes is hinged on pretinning. Pre-dip soldering tends to reduce the number of defective joints. Labor intense reworking can be eliminated. Computer programmed transporting and dipping movements may be used in conjunction with a range of units designed to generate a surface solder coating. Dip soldering is also used to join complete assemblies combining a conveyor and dipping mechanisms with a solder bath and flux tank (12).

Drag soldering uses a stationary bath of liquid solder less than 2 inches deep (12). A drag soldering apparatus is shown in Figure 2. The solder bath contacts the board at a slight angle, then the board levels out with the underside of the board contacting the solder. The board exits at an angle in order to drain extra solder from the board. The pattern of conductor tracks is also important for drainage in drag soldering since improved drainage takes place when the tracks are parallel to the board motion (12).

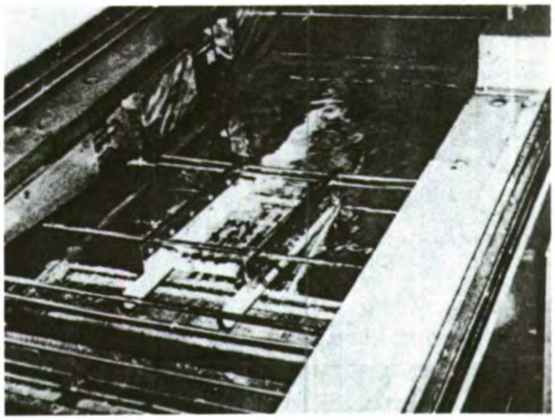

Figure 2. Drag soldering apparatus

Wave soldering typically produces clean, oxide-free bright surfaces of solder. A wave soldering apparatus is shown in Figure 3. Wave soldering is a process where molten solder is pumped vertically upwards through a narrow slot and forms a steady waterfall or wave. Wave soldering equipment allows the printed circuit board to be loaded on a conveyor carrying it through the various stages of the soldering operation. Subsequent cleaning of the board after the wave soldering process should remove flux and other residues. A cleaning unit may be added in-line so that the printed circuit board passes through it immediately after the soldering operation or an operator may manually move the board to a separate cleaning unit (12).

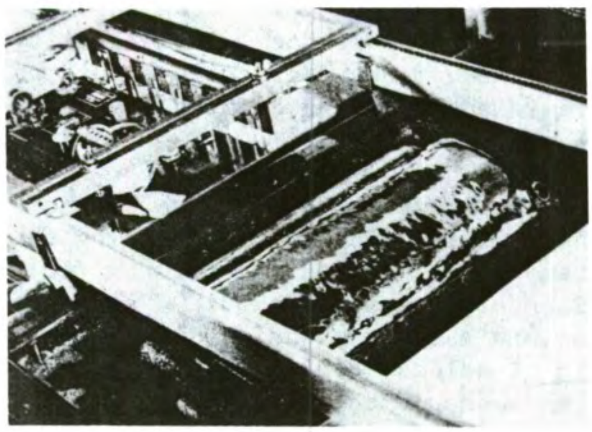

Figure 3. Wave soldering apparatus

Vapor phase soldering supplies heat in a unique fashion to a reflow soldering process (12). The vapor phase soldering process is shown in Figure 4. Solid solder preforms are melted by an atmosphere of hot saturated vapor generated by a boiling reservoir of a special inert liquid. When the workpiece is lowered into the area of vaporized inert substance, the vapor condenses on the solder joint, melting the solder and forming the joint (12).

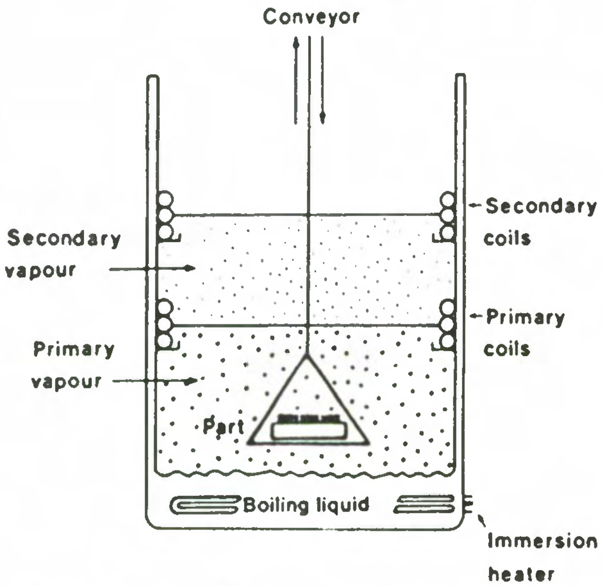

Figure 4. The vapor-phase process

Carefully controlling the soldering process is important for elimination of manual repair to faulty joints (12). Soldering temperature, flux, and soldering time, as well as the control of trace impurities in the solder, are important parameters and have marked effects on the solder quality (12).

Among the many soldering processes, there is no singularly acceptable one. The requirement for a predictable and consistent equipment life is the driving concern. The application of one government defined and edicted process is inappropriate. There are many sources, including military specifications and standards, industry standards, and technical literature that should be used in establishing an effective controllable soldering process.

ACCELERATED FATIGUE TESTING

<u>What guidelines should be used when accelerated fatigue testing is considered?</u>

Accelerated reliability testing may provide a measure of solder joint fatigue reliability to validate manufacturing processes and controls. The purpose of the testing may include process verification and the acquisition of surface mount solder fillet reliability measurements (4). The mixture of tensile and shear fatigue accelerated testing may provide rapid failure of substandard solder joints. The test should simulate operating conditions without introducing unrepresentative failure mechanisms. Physical and/or material characteristics should approximate reality as much as possible. Then the results of testing will more accurately represent the reliability of the product. The amount of test acceleration influences the validity of the result and provides a high ratio of actual product life to accelerated test mean time to failure (4). Table 1 provides a summary of some accelerated fatigue test parameters.

In functional or temperature testing, defined dwells at temperature extremes are necessary, and should be at least 25 percent of the cycle period in duration (4). Functional accelerated testing is the most representative test environment and does not introduce differences between accelerated tests and product actual use. In functional testing the conditions mimic the functional use conditions and the actual product as closely as possible except for the reduced test

dwell times and the cyclic frequency. The shortened dwell times (4) lead to a lower conversion of elastically stored strain energies to plastic deformations via stress relaxation and creep. Lower fatigue damage per cycle results in a longer fatigue life. However, the actual time necessary to produce failures is reduced since the total test time is shortened. Thermal cycling gives reduced accuracy and simpler test arrangements. Isothermal mechanical cycling provides only very coarse data (4).

The test assemblies should be representative of the actual product (size, type of component, materials, etc.) and provide typical product variations (4). Intentional variations such as solder volume irregularities and misalignment are desirable. Solder should be similar in grain structure composition, and intermetallic compound layers. Solder grain structure is unstable since it coarsens with cyclic strain from temperature changes and other environmental cycles (4).

A possible accelerated aging technique used on test articles requires 30 hours at 100 degrees Celsius in air (4). Storing the test articles at room temperature will stabilize the microstructure of the solder. Dwell durations at the extreme temperatures should be 3 to 5 minutes for functional and thermal cycling (5). The dwell durations may be hours or days for the actual product. Mechanical cycle durations can be as low as 3 seconds.

QUALITY ASSURANCE OF SOLDER JOINTS

<u>What are the available methods of non-destructive inspection and assurance of quality in solder joints?</u>

Non destructive inspection completed by humans has the reputation of being expensive and very inconsistent thereby making the use of automated non-destructive inspection highly attractive (12). The automated screening methodologies reduce the incidence of poor connections and decrease manual labor. Critical defect detection includes a number of approaches including automated printed wiring assembly inspections. Reliability of solder connections is important for avionic system operation and availability. Many thousands of connections can be screened with automated equipment. Additionally, automated techniques can generate feedback information needed to control automated manufacturing processes (13).

Automated techniques include laser-IR systems and automated X-ray systems. The laser-IR system operates through heating the solder joint connection, observing the buildup and decay of the solder joint temperature waveform and then comparing it to a statistical spread of data from known boards (13). The key to applying the above techniques is the development of appropriate control limits that assure the delivered product fulfills life requirements but does not necessitate unnecessary rework.

SUMMARY

Stress relaxation and creep take place in solder through conversion of elastic strains to plastic strains. The conversion is accelerated by higher temperatures and stress levels. Short intermittents are the first indications of minute fatigue cracks in solder joints. The growth of these fatigue cracks is known as accumulation of cyclic fatigue damage and is used to predict solder joint fatigue life. The source of the fatigue cracks are plastic deformations re-

sulting from stress relaxations which take place at most use temperatures. A design challenge lies in preventing fatigue failures through elimination of mismatches of coefficients of thermal expansion between boards, solder, and components. Power dissipations provide a further challenge since thermal gradients lead to board warpage. Other factors also influence the life of solder joints. Life prediction models for solder are available to assist in predictions of avionic system life. Design criteria such as alignment and pretinning of components affect the fatigue life of solder. Manufacturing processes and quality assurance practices also influence solder joint life. Accelerated fatigue testing may be used as criteria for prediction of surface mount solder joint life. Issues that need to be carefully assessed surrounding reliability in surface mount solder joints for the achievement of avionics integrity are fatigue in surface mount devices, castellations and surface finish issues, life predictions, design criteria, manufacturing processes and controls, accelerated fatigue testing, and quality assurance of solder joints.

Table 1. Typical Accelerated Fatigue Test Parameters (4)

Test	Temperature	Frequency	Warpage	Acceleration Factors	Comments
Functional	Realistic	LT 100 cyc/day LT 30 deg/min defined dwells	Realistic	10 to 20	Realistic Power and Heat Transfer
Temperature	0-100 C 20-100 C -55 -80 C	LT 24 cyc/day T rate LT 30 deg C/min defined dwells	Somewhat higher than realistic	LT 1 to 10 LT 30 with deliberate test vehicle	Very long test durations for delta CTE LT 5 PPM per deg C
Mechanical	Isothermal (0 deg C, RT, 60 deg C, 80 deg C)	LT 10,000 cyc/day near square wave somewhat	Bend radius 40 to 80 inches	LT 500	Excludes all CTE mismatch effects; higher tensile strains beware of over-strain

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